Soil Carbon Pools, Nitrogen Supply, and Tree Performance under Several Groundcovers and Compost Rates in a Newly Planted Apple Orchard

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***Abstract*. This study evaluated the effects of in-row groundcovers (bare ground, brassica seed meal, cultivation, wood chip mulch, legume cover crop, and non-legume cover crop) and three compost rates (48, 101, and 152 kg available nitrogen (N)/ha/year) on soil carbon (C) pools, biological activity, N supply, fruit yield, and tree growth in a newly planted apple (*Malus domestica* Borkh.) orchard. We used nonlinear regression analysis of C mineralization curves to differentiate C into active and slow soil C pools. Bare ground and cultivation had large active soil C pools, 1.07 and 0.89 g C/kg soil, respectively, but showed little stabilization of C into the slow soil C pool. The use of brassica seed meal resulted in increased soil N supply, the slow soil C pool, and earthworm activity but not total soil C and N, fruit yield, or tree growth. Legume and non-legume cover crops had increased microbial biomass and the slow soil C pool but had lower fruit yield and tree growth than all other groundcovers regardless of compost rate. Soils under wood chip mulch had elevated earthworm activity, total soil C and N, and the slow soil C pool. Wood chip mulch also had the greatest cumulative C mineralization and a high C:N ratio, which resulted in slight N immobilization. Nevertheless, trees in the two wood chip treatments ranked in the top four of the 13 treatments in both fruit yield and tree growth. Wood chip mulch offered the best balance of tree performance and soil quality of all treatments.**

Organic apple production has seen rapid expansion over the past 20 years because of consumer demand for fruit that has not been treated with synthetic fertilizers or pesticides and price premiums that growers can get for organic apples (Granatstein and Kirby, 2007; Kirby and Granatstein, 2009). Organic apple production uses compost and other organic fertilizers to supply nutrients to trees over the growing season. These organic sources are often considerably more expensive (Granatstein and Mullinix, 2008) and release N slowly, which can result in lower yields and low leaf and fruit tissue N levels compared with conventional apple systems (Delate et al., 2008). Improving organic fertilizer-use efficiency is critical to increasing cost efficiency in organic apple production. Integrating organic mulches and cover crops into apple production systems has been proposed to improve yields, nutrient availability, and long-term orchard sustainability (Granatstein and Mullinix, 2008).

Organic mulches, cover crops, and organic fertilizers such as compost may add large amounts of organic C (OC) to the soil. Decomposition and nutrient release from these additions can enhance soil quality by increasing soil C, N, and microbial biomass and changing the composition of the soil microbial community (Laakso et al., 2000; Wardle et al., 2001). However, improvements in soil quality have not always translated into improved leaf and fruit N levels or greater yields. For example, legume and non-legume cover crops have increased soil N availability and microbial activity but decreased tree growth or yield, presumably as a result of competition between trees and cover crops (Hoagland et al., 2008a; Marsh et al., 1996; Neilsen and Hogue, 1985; Sanchez et al., 2003). Organic mulches such as wood chips, shredded paper, and alfalfa have been shown to increase soil microbial activity and N turnover, increasing N availability, fertilizer-use efficiency, and fruit yield in some studies (Forge et al., 2003; TerAvest et al., 2010; Yao et al., 2005), although N immobilization and N deficiency have also been reported (Larsson et al., 1997). Brassica seed meals used as a soil amendment may serve as an organic source of N (Balesh et al., 2005) and a biological control for pathogens and weeds (Cohen and Mazzola, 2006; Hoagland et al., 2008b).

Herbicides and cultivation to maintain bare ground within tree rows are the most common practices in conventional and organic apple production, respectively. Although inexpensive, these systems may have detrimental effects on soil C, N, and the soil microbial community, reducing soil quality and nutrient availability (Cambardella and Elliot, 1992; Sanchez et al., 2003, 2007; Van Den Bossche et al., 2009). Soil disturbance also reduces earthworm populations and root colonization by arbuscular–mycorrhizal (AM) fungi (Boddington and Dodd, 2000; Bohlen et al., 1999). Both earthworms and AM fungi have been shown to improve soil quality and nutrient cycling. Earthworms help incorporate surface litter into the soil increasing organic N levels and N mineralization and may alter the soil microbial community structure (Aira et al., 2008; Beare, 1997; Whalen et al., 2001). Arbuscular–mycorrhizal fungi play a critical role in soil nutrient cycling, assisting in nutrient uptake and decomposition of recalcitrant organic residues, and increasing aggregate stability and soil structure (Barea et al., 2005).

In this study, we examined how groundcover management would affect soil N supply and soil C dynamics. Changes in orchard management may not have a significant effect on total soil C or soil organic C content for years, whereas labile soil C pools respond more rapidly to changes in management (Haynes, 2005; Reganold et al., 2001). Therefore, we measured CO_2 evolution from long-term (160-d) laboratory incubations of soil to biologically separate soil C into the active soil C pool (C_a) and the slow soil C pool (C_s) to determine groundcover management effects

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on soil C pools (Collins et al., 2000). The C_a and C_s influence microbial activity, nutrient cycling, soil fertility, and ecosystem sustainability (Paul et al., 1999). The C_a consists of labile C (simple sugars, organic acids, microbial biomass, and metabolic compounds from soil amendments and cover crops) derived from recent organic matter additions (Cochran et al., 2007). This pool has a rapid turnover time, acts as a readily available substrate for the microbial community, and can have a wide C:N ratio depending on the source, possibly leading to N immobilization during C mineralization (Cochran et al., 2007; Compton and Boone, 2002; Hooker and Stark, 2008). Conversely, C_s-C is a heavier C fraction with a narrower C:N ratio, is physically stabilized, has a turnover rate of weeks to months, and can act as an N source (Cochran et al., 2007; Whalen et al., 2000). The resistant C pool (C_r) is a C from a combination of residues that are biochemically recalcitrant and physically protected from decomposition, which serves to stabilize soil aggregates but does not significantly affect soil fertility (Cochran et al., 2007; Paul et al., 2006).

Accurately estimating soil N supply is difficult and many methods have been proposed (Jalil et al., 1996; Sharifi et al., 2007a, 2007b). In this study, N supply includes N derived from organic amendments (compost, brassica seed meal, wood chip mulch, and cover crops) and residual soil N from previous growing seasons. Measuring only inorganic N (NO_3^- + NH_4^+) would not accurately reflect soil N supply, because release of N from organic amendments is driven by soil microbial processes, and N may be mineralized and immobilized by microorganisms simultaneously (Haynes, 2005). Laboratory incubations measuring N mineralization over the length of the growing season could overestimate N mineralization because ideal soil conditions are used and would at best represent the maximum potential N mineralization (Haynes, 2005). Nitrogen mineralized from a short-term (14-d) anaerobic incubation represents a readily available labile N pool that has been strongly correlated with inorganic N (Sharifi et al., 2007a). The combination of inorganic N and N mineralized from a short-term anaerobic incubation has been proposed as a good predictor of soil N supply (Sharifi et al., 2007b). In this study we used N mineralized from 7-d anaerobic incubation plus inorganic N to estimate soil N supply at three times during the growing season.

The objectives of this study were to examine the impacts of groundcover management and compost rate on C mineralization and partitioning of C into different pools, soil biological activity, soil N supply, total soil C and N, and tree performance. Tree performance parameters included fruit yield, tree growth, yield efficiency, and leaf N concentration.

Materials and Methods

Study site. This study was established in Spring 2005 at the Wenatchee Valley College Auvil Teaching and Demonstration Orchard in East Wenatchee, WA. Soil at the study site is a Pogue sandy loam (coarse-loamy over sandy or sandy-skeletal, mixed, superactive, mesic Aridic Haploxerol) averaging 1% to 2% organic matter and a pH of 7.0. Annual precipitation at the orchard site averages 21.6 cm. The study site was previously planted to sweet cherry trees, which were removed in 2004. In 2005, after stump removal and disking, apple trees (cv. Pinata on EMLA 7 rootstock) were planted at a spacing of 1.5 m within the tree row and 4 m between rows (1541 trees/ha). Individual plots were arranged in a randomized complete block design with five replicates of 13 treatments. Each treatment was a combination of groundcover management and compost rate. Each plot consisted of a row of eight trees: six study trees with a guard tree at each end. Unfertilized control plots consisted of only three trees as a result of space constraints, all of which were used for measurements. Trees were irrigated as needed throughout the growing season with under-tree microsprinklers (R-10 rotators; Nelson Irrigation, Walla Walla, WA). The site was organically certified for the first 2 years of the study, but the organic certification was removed in 2007 to allow for synthetically derived herbicides because the orchard was scheduled to be removed on completion of the study. With the exception of herbicide use in the third year of the study, the orchard was organically managed throughout the study.

Groundcover management. Groundcover management was established in a 1.5-m wide strip centered on the tree row with a 2.5-m drive alley between rows planted to perennial grasses. Seven groundcover treatments were used (Table 1): 1) unfertilized control (CON); 2) bare ground (BG); 3) brassica seed meal amendment (BSM); 4) mechanical cultivation (CLT); 5) wood chip mulch (WC); 6) legume cover crop (LC); and 7) non-legume cover crop (NLC). Bare ground was maintained in CON, BG, and BSM with the combination of cutting weeds at ground level with a string trimmer, shallow hoeing, and applications of a clove oil-based organic herbicide (Matran™; Ecosmart Technologies, Franklin, TN; 20% solution) as needed in 2005 and 2006. As a result of difficulty controlling weeds with these methods and the planned removal of the orchard, weeds were controlled by spot spraying with post-emergent glyphosate (1% solution) starting in May 2007. In all years, mechanical cultivation consisted of

Table 1. Treatment abbreviations, compost rates, and groundcover managements.

Groundcover	Abbreviation	Compost[z] Rate	Compost[z] Total C (kg/ha/year)	Compost[z] Available N (kg/ha/year)	Groundcover management
Control	CON	None	None	None	Undisturbed bare ground: Matran™, hand weeding, and glyphosate
Bare ground	BG	MCR[y]	1890	101	Undisturbed bare ground: Matran™, hand weeding, and glyphosate
Brassica seed meal	BSM	LCR	1160	62	Undisturbed ground: Matran™, hand weeding, and glyphosate + 1136 kg/ha/year *Sinapis alba* seed meal
Cultivation	CLT	LCR	900	48	Tilled bare ground: tilled 4× per season
		MCR	1890	101	
		HCR	2860	152	
Wood chip mulch	WC	MCR	1890	101	15-cm layer of mixed deciduous and coniferous wood chips applied each April
		HCR	2860	152	
Legume cover	LC	LCR	900	48	Mix of birdsfoot trefoil, Colonial bentgrass, Mt. Barker subterranean clover, black medic, and burr medic
		MCR	1890	101	
Non-legume cover	NLC	LCR	900	48	Mix of sweet alyssum, five spot, mother of thyme, and Colonial bentgrass
		MCR	1890	101	
		HCR	2860	152	

[z]Compost rates listed for the 2006 and 2007 seasons.
[y]LCR = low compost rate; MCR = medium compost rate; HCR = high compost rate.
C = carbon; N = nitrogen.

using a Wonder Weeder cultivator (Harris Manufacturing, Burbank, WA) four times per season on the sides of the trees and rototilling between the trunks as needed to a depth of 5–8 cm of soil. Wood chip mulch plots had a 15-cm layer of mixed conifer and deciduous wood chips (1.3 × 2.5 cm maximum size) applied once per season in the spring of all years. In 2005 and 2006, weed escapes were hand pulled, and starting in May 2007, glyphosate (1% solution) was spot sprayed as needed.

The legume and non-legume cover crops were planted in 2005 at rates of 38.4 $kg \cdot ha^{-1}$ and 38.2 $kg \cdot ha^{-1}$, respectively. The legume cover crop included a mix of Mt. Barker subterranean clover (*Trifolium subulata*; Ampac Seed Co., Tangent, OR; 25.6%), black medic (*Medicago lupulina*; Big Sky Seed, Shelby, MT; 12.2%), burr medic (*Medicago polymorpha*; Kamprath Seed Co., Manteca, CA; 25.9%), birdsfoot trefoil (*Lotus corniculatus*; Ampac Seed Co., 30.9%), and Colonial bentgrass (*Argostis tenuis*; Grassland West, Clarkston, WA; 5.3%). Grass species were included in the legume cover crop mix to enhance C production. The non-legume cover crop included a mix of sweet alyssum (*Lobularia maritime*; Germain Seeds, Fresno, CA; 70.4%), five spot (*Nemophilia maculate*; Outside Pride, Independence, OR; 8.2%), mother of thyme (*Thymus serpyllum*; Outside Pride; 3.9%), and Colonial bentgrass (17.6%). Legume and non-legume species for these mixes were chosen based on prior research on potential cover crop species (Granatstein, personal communication). The drive-alley, legume cover crop, and non-legume cover crop were mowed as needed with clippings left on the ground.

Organic nitrogen amendments. Organic N amendments were applied at low (LCR), medium (MCR), and high (HCR) rates. The MCR was based on the optimum N rate, ≈60 g N/tree/year for establishing newly planted apple trees with similar rootstock (Fallahi et al., 2001) and was applied to BG, BSM (in 2005), CLT, WC, LC, and NLC. As a result of space constraints, the LCR was applied only to CLT, LC, and NLC and the HCR was only applied to CLT, WC, and NLC.

In Spring 2005, pelleted chicken manure (NutriRich, Stutzman Farm, Canby, OR; 4% N, 28% available after a 14-d anaerobic incubation) was broadcast in tree rows at 56, 111, and 166 kg total N/ha for the LCR, MCR, and HCR, respectively, and incorporated before tree planting. As a result of poor initial tree growth, an additional 2.75 kg total N/ha/week was applied equally to all treatments starting in June and continuing throughout the summer as a weekly foliar application of fish emulsion and kelp (Mermaids; I.F.M., Wenatchee, WA; Acadian Seaplants, Dartmouth, Nova Scotia, Canada). A soluble N fertilizer of fermented plant and animal waste (Biolink; Westbridge Ag Products, Vista, CA; 14% N) was also injected (using a handmade injector consisting of a steel pipe with a trigger to release the fertilizer) below each tree (30 cm from the tree trunk, 15 cm depth) at 18, 36, or 54 kg total N/ha in mid-July for the LCR, MCR, and HCR, respectively.

In 2006 and 2007, Nielsen's chicken manure compost (Mossyrock, WA; 3.5% N, 51% available in a 14-d anaerobic incubation, C:N ratio ≈8:1) was used because N was more readily available than in the pelleted chicken manure. Additionally, the N application rate was increased from 60 g total N/tree/year to 60 g available N tree/year in 2006 and 2007 to improve tree growth. Compost was applied in a band around the base of each tree 15 to 30 cm from the trunk at 48, 101, and 152 kg available N/ha/year for the LCR, MCR, and HCR, respectively. Compost was left on the surface in all treatments except CLT, where it was incorporated when the plots were tilled for weed control. Compost was applied in four split applications (7 Apr., 9 May, 25 May, and 7 June) in 2006 and in three split applications (25 Apr., 25 May, and 21 June) in 2007. In 2006 and 2007, BSM plots were given a reduced rate of compost, 62 kg available N/ha/year, because we expected N release from the seed meal. Seed meal derived from the yellow mustard *Sinapis alba* cv. Ida Gold (J. Brown, University of Idaho; 7% N) was broadcast over BSM plots at a rate of 79.5 kg total N/ha/year in 2005 (May), 2006 (equal applications in May, June, and July), and 2007 (equal applications in April, May, and June). Brassica seed meal was incorporated into the soil to a depth of 1–2 cm using a rake in May 2005, May 2006, and June 2006. The July 2006 and all 2007 BSM applications were left on the soil surface to reduce soil disturbance.

Sampling and analysis. Carbon mineralization, C pool differentiation, and soil biological responses were analyzed for CON, BG, and BSM and the medium compost rates of CLT, WC, LC, and NLC only to focus on groundcover management affects. Soil N supply, total C (TC) and N, and tree performance were analyzed for all groundcovers and compost rates. Soil samples were collected in April each year (before compost application) and again in July and September by taking one core per tree with a 2-cm diameter probe (0- to 10-cm depth), 15–30 cm from the base of each tree (beneath the band of compost), and composited into one sample per plot. Additional soil cores (15-cm diameter; 0- to 10-cm depth), specifically for earthworm population density, and AM fungi root colonization were taken from three trees per plot in Sept. 2007. April and July soil samples were oven-dried at 105 °C for 24 h and then passed through a 2-mm sieve. September samples were passed through a 2-mm sieve and stored at 4 °C until analysis. Soils from all sampling dates were analyzed for inorganic N (NO_3^- + NH_4^+) and readily mineralizable N. Soil samples were mixed with deionized water at 1:2.5 (w/v) and incubated at 40 °C for 7 d (Schmidt and Belser, 1994). Concentrations of NO_3^- and NH_4^+ in both initial and incubated samples were determined after extraction with 1 M KCl using a continuous-flow colorimetric analyzer (300 series; Alpkem, OR). Readily mineralizable N was calculated by subtracting the initial amount of available N from that present after incubation.

September soil samples were analyzed for total N and C using a dry combustion analyzer (Costech, Valencia, CA) in 2005 and 2007, and 2007 samples were also analyzed for dehydrogenase activity (Tabatabai, 1994) and substrate-induced respiration (SIR) (Anderson and Domsch, 1978). The 15-cm soil cores were hand sorted to visually determine earthworm population density and collect apple tree roots. Apple tree roots recovered from soil cores were cleared, dyed (0.4% Trypan blue solution), and AM fungi root colonization was quantified using the grid-line intersect method (Reich and Barnard, 1984).

In 2007, fruit were thinned to 5 fruit/cm^2 trunk cross-sectional area (TCSA) in June. In July, four leaves were sampled from the middle third of each sample tree, composited by plot, oven-dried at 50 °C for 48 h, ground, and analyzed for N concentration using a dry combustion analyzer. In September, TCSA was calculated from tree circumference measurements taken 20 cm above the graft union, fruit were harvested, and yield efficiency was calculated (kg yield/cm^2 TCSA).

Modeling carbon pools. Laboratory incubations of 160 d were used to generate C mineralization curves for soils sampled in Sept. 2007. Soils were sieved to 2 mm, adjusted to 60% water-holding capacity, and incubated at 20 °C (Robertson et al., 1999). Evolution of CO_2 was measured at 1-week, and later 2-week, intervals with a gas chromatograph (Shimadzu, MD). Carbon mineralization curves were used to determine C_a pool size, C_a pool turnover rate (k_a), C_s pool size, and C_s pool turnover rate (k_s) (Collins et al., 2000; Paul et al., 1999). Carbon pool size and turnover rate were estimated by curve fitting CO_2 evolution per unit time (C_t) using a constrained three-pool first-order model:

$$C_t = C_a e^{-k_a t} + C_s e^{-k_s t} + C_r e^{-k_r t}$$

A nonlinear regression model (Systat Software Inc., Richmond, CA) was used to estimate C_a, k_a, and k_s. The slow pool was defined as $C_s = TC - C_r - C_a$. Resistant pool C is not released in a significant quantity in 160-d incubation (Paul et al., 1999); therefore, C_r was determined using acid hydrolysis with soil refluxing in 6 M HCl (Paul et al., 2001) and was defined as the non-hydrolyzable fraction of soil C. Mean residence time (MRT), the average time that soil C resides in a given pool, was the reciprocal of the decomposition rate constants (k^{-1}), and was scaled to field MRT by assuming a Q_{10} of 2, [$2^{(20-t)/10}$], where the mean annual temperature (t) is 10.5 °C.

Statistical analysis. Statistical analyses were conducted using SAS 9.1 software (SAS Institute, Cary, NC). Groundcover management and compost rate effects on cumulative C mineralization, soil N supply, total C and N, soil biology, and tree performance were analyzed with one-factor analysis of variance of a completely randomized block design. Each groundcover + compost rate combination was analyzed as an individual treatment. Mean separation was based on Fisher's protected least significant difference and differences were considered significant at $P \leq 0.05$.

Results

Additions of OC through compost, wood chip, and brassica seed meal applications or cover crops increased cumulative C mineralization after 160 d in all treatments compared with CON (Fig. 1A). Wood chip mulch mineralized the most C, 999 mg CO_2-C/kg soil, significantly greater than BSM and CON, 538 and 456 mg CO_2-C/kg soil, respectively. Cultivation and NLC mineralized 843 and 828 mg CO_2-C/kg soil, respectively, also significantly more than CON. When expressed on a soil C basis instead of a total soil mass basis, CLT (64.9 g CO_2-C/kg soil C), NLC (61.5 g CO_2-C/kg soil C), and BG (60.9 g CO_2-C/kg soil C) had higher rates of C mineralization than WC (55.5 g CO_2-C/kg soil C), although there were no significant differences among groundcovers (Fig. 1B).

Non-linear regression analysis of C mineralization curves resulted in R^2 values ranging from 0.92 to 0.98 for observed vs. predicted mineralization curves (Fig. 2). A sharp change in CO_2-C evolution rate often denotes the boundary between active and slow C pools. This change occurred between 20 and 40 d for BSM, WC, LC, CON, NLC, and CLT, whereas there was no sharp change in slope in the BG soil, which had a low initial CO_2-C evolution rate (Fig. 2C). Wood chip, CLT, and BG had large C_a pools and MRT compared with other treatments, whereas WC also had the largest C_s pool and MRT, 7.82 g C/kg soil and 24.3 years, respectively (Table 2). Bare ground followed by CLT had a large proportion of C in the C_a (9% and 7% of TC, respectively) and C_r (70% and 62% of TC, respectively) pools but had a small proportion of C_s-C (21% and 31% of TC, respectively). In contrast, BSM, LC, and NLC had smaller C_a pools but larger C_s pools. Mean residence time was low in CON, NLC, and LC for the C_s pool and low in LC and CON in the C_a pool. Between NLC and LC, NLC had greater C_a-C and C_s-C and longer MRT for both pools. In this study, MRT was strongly correlated with pool size for the C_a pool (R^2 = 0.89) but not with the C_s pool (R^2 = 0.27) (data not shown).

Wood chip mulch and BSM yielded high extrapolated earthworm densities of 430 and 355 m^{-2}, respectively (Table 3), significantly greater than CLT (143 m^{-2}) and BG (102 m^{-2}), which were significantly greater than NLC (11 m^{-2}). Non-legume cover had the greatest AM fungi root colonization at 36%, significantly higher than all other groundcovers. The CON also had high AM fungi root colonization (21.9%), significantly greater than both CLT (7.2%) and BSM (5.6%). Microbial biomass, as measured by SIR, was greater in LC and NLC than all other groundcovers, which were similar. Dehydrogenase activity was not statistically different among treatments.

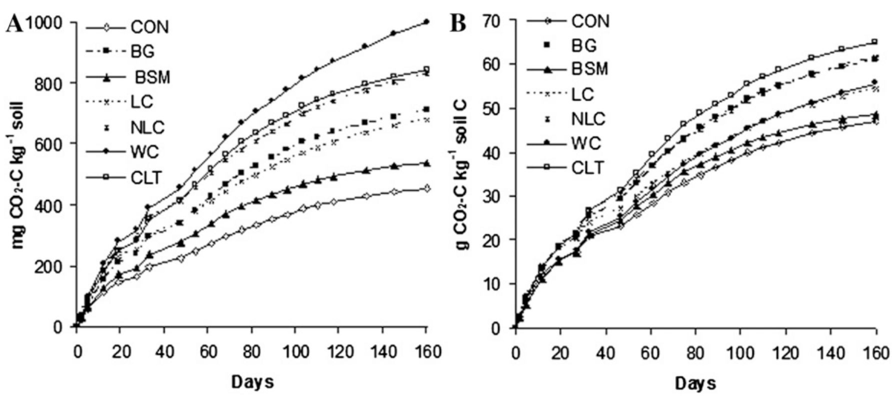

Fig. 1. Cumulative CO_2-C mineralized during extended laboratory incubation expressed as: (**A**) mg CO_2-C/kg soil, (**B**) g CO_2-C/kg soil C. CON = control; BG = bare ground; BSM = brassica seed meal; LC = legume cover; NLC = non-legume cover; WC = wood chips; CLT = cultivation.

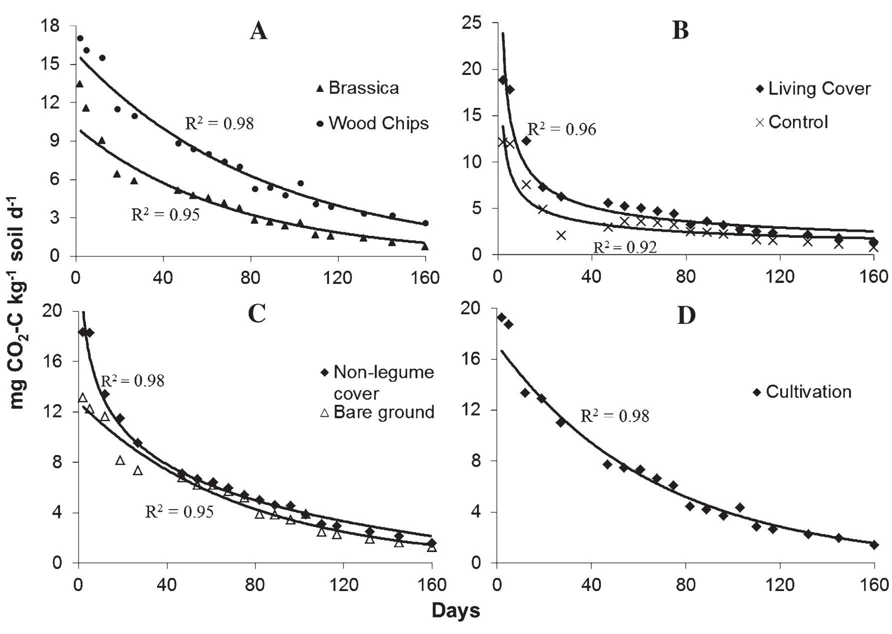

Fig. 2. Rate of CO_2-C evolution during extended laboratory incubation for: (**A**) brassica seed meal and wood chips, (**B**) living cover crop and control, (**C**) non-legume cover crop and bare ground, and (**D**) cultivation. R^2 values reflect observed vs. predicted CO_2 evolution curves.

In July and Sept. 2006, N supply was significantly greater in BSM and LC_{MCR} than CON, WC_{HCR}, and WC_{MCR} (Table 4). In April 2007, N supply was elevated in NLC_{HCR}, BSM, CLT_{HCR}, NLC_{MCR}, and LC_{MCR}. In Sept. 2007, N supply in NLC_{HCR} was greater than in all other treatments except CLT_{HCR}. Total soil C content was greater in WC_{HCR}, NLC_{HCR}, WC_{MCR}, and CLT_{HCR} than all other treatments except NLC_{MCR} and LC_{MCR} and corresponded with large increases in total C and N from 2005 to 2007 (Table 5). Total soil N content was greater in NLC_{MCR}, WC_{MCR}, and CLT_{HCR} than all other treatments except WC_{MCR}. In addition to large total C and N content in the WC treatments, the soil C:N ratios of these treatments were significantly greater than other treatments. Total soil C and N increased with compost application rate in the CLT and NLC groundcovers.

Nitrogen supply in BSM was consistently elevated relative to BG, except in Apr. 2006 and Sept. 2007 (Table 4). Total soil C and N and C:N ratio were similar among BSM, BG, and CON. In CLT, N supply and total C and N generally did not increase over CON at the low and medium compost rates. However, at the high rate, total C and N (Table 5) and N supply in July 2006 and Sept. 2007 (Table 4) were greater than CON. Total C and N in NLC and LC receiving low and medium compost rates did not differ and were significantly lower than NLC_{HCR}.

Fruit yields in CLT_{HCR} and WC_{HCR} were significantly greater than CLT_{MCR}, BG, and BSM, which in turn were greater than CON, LC, and NLC regardless of compost rate (Table 6). Tree growth (TCSA) was larger in CLT_{HCR}, WC_{MCR}, CLT_{LCR}, and WC_{HCR} than all LC and NLC treatments. Yield efficiencies in CLT_{MCR}, WC_{HCR}, CLT_{HCR}, BG, BSM, and WC_{MCR} were greater than all cover crop treatments except NLC_{HCR}. Leaf N was adequate for young fruit-bearing apple trees regardless of treatment (Stiles, 1994) but was lower in NLC_{LCR} than all other treatments except CON.

Table 2. Concentration, percent of total C (TC), and mean residence time (MRT) for the active (C_a), slow (C_s), and resistant (C_r) soil C pools ± (SE) as affected by groundcover management in Sept. 2007.[z]

	Active C			Slow C			Resistant C
Groundcover[y]	g C/kg soil	C_a/TC (%)	Field MRT (d)	g C/kg soil	C_s/TC (%)	Field MRT (years)	C_r/TC (%)
Control (CON)	0.16 (0.24)	1.63	25 (4.7)	4.24	43.7	9.6 (1.2)	55
Bare ground (BG)	1.07 (0.32)	9.05	161 (36)	2.44	20.7	16.1 (8.1)	70
Brassica (BSM)	0.45 (0.86)	3.92	76 (13)	5.69	49.8	22.8 (9.2)	46
Cultivation (CLT)	0.89 (0.13)	6.84	96 (12)	4.08	31.2	17.3 (10)	62
Wood chips (WC)	0.96 (0.17)	5.41	120 (16)	7.82	44.0	24.3 (12)	51
Legume (LC)	0.31 (0.37)	2.41	33 (4.6)	4.69	36.9	7.6 (0.9)	61
Non-legume (NLC)	0.63 (0.08)	4.59	75 (9.0)	6.32	46.0	9.0 (1.8)	50

[z]Modeling C partitioning into different pools required combining all replicates; therefore, we were unable to do traditional analysis of variance on the data presented in this table. Statistical analysis for non-linear regression analysis of the C mineralization curves used to model C pools is presented in Figure 2.
[y]Groundcovers BG, CLT, WC, LC, and NLC at medium compost rate, BSM at low rate, and CON with no compost.
C = carbon.

Table 3. Soil biological responses to groundcover management in Sept. 2007.[z]

Groundcover	Earthworms (no./m^2)	AM fungi root infection (%)	SIR[y] (µg C/g soil)	Dehydrogenase (µg TPF/h)
Control (CON)[x]	26 cd	21.9 b	1936 b	2.63 a
Bare ground (BG)	102 bc	14.2 bc	1962 b	4.43 a
Brassica (BSM)	355 a	5.6 c	1947 b	2.37 a
Cultivation (CLT)	143 b	7.2 c	1999 b	2.29 a
Wood chip (WC)	430 a	13.4 bc	1945 b	5.84 a
Legume cover (LC)	45 bcd	11.5 bc	2089 a	5.02 a
Non-legume cover (NLC)	11 d	36.0 a	2123 a	5.72 a

[z]Values within a column followed by the same letter are not significantly different ($P \leq 0.05$).
[y]Substrate induced respiration.
[x]Groundcovers BG, CLT, WC, LC, and NLC at medium compost rate, BSM at low rate, and CON with no compost.

Table 4. Soil N supply: NO_3^- + NH_4^+ + readily mineralizable N in April, July, and September for 2006 and 2007 as affected by groundcover and compost rate.[z]

		2006[y]			2007		
	Compost	April	July	September	April	July	September
Groundcover	rate	mg N/kg soil					
Control	None	29.4 a	36.9 c	41.4 bcdef	74.3 cde	33.4 a	36 f
Bare ground	MCR[x]	25.7 a	44.7 bc	45.9 abcde	56 de	43.9 a	54.2 cdef
Brassica	MCR	25.6 a	64.9 a	58.1 a	99.6 ab	77.7 a	49.7 def
Cultivation	LCR	20.4 a	37.1 c	32.3 ef	53.2 e	54.2 a	45.5 ef
	MCR	18.4 a	55.4 abc	35.5 def	68.1 de	49.3 a	51.4 def
	HCR	20 a	57.3 ab	37.3 def	94.7 abc	54.6 a	92.8 ab
Wood chips	MCR	23.8 a	44.5 bc	34.1 ef	77.6 bcd	39.7 a	59 cdef
	HCR	28.9 a	37.4 c	28.2 f	58.8 de	48.8 a	79 abc
Legume cover	LCR	23.1 a	59.1 ab	44.9 abcde	69.3 de	61.5 a	55.9 cdef
	MCR	21.2 a	66.4 a	55.5 ab	94.5 abc	78.2 a	61.5 cde
Non-legume	LCR	34 a	54.2 abc	44.7 abcde	73.5 cde	47.9 a	48.9 def
Cover	MCR	27.6 a	53.9 abc	51.5 abc	94.7 abc	46.1 a	70 bcd
	HCR	37.5 a	55.5 abc	49.5 abcd	117.9 a	71.5 a	96.6 a
Mean		25.8	51.3	43.0	79.4	54.4	61.6

[z]Means within the same column with the same letter are not significantly different ($P \leq 0.05$).
[y]Nitrogen supply data for 2006 are from Hoagland (2007) and Hoagland et al. (2008a) and are repeated here for comparison with the 2007 data.
[x]HCR = high compost rate; MCR = medium compost rate; LCR = low compost rate.
N = nitrogen.

Discussion

Sizeable yearly additions of compost and wood chip mulch resulted in the greatest C mineralization and large C_a and C_s pools. However, the high C:N ratio of the wood chip mulch increased the C:N ratio of soils in WC and reduced the rate of C mineralization on a soil C basis. Both WC and BSM had significant stabilization of C into the C_s pool, which may increase N mineralization and improve long-term C storage under these groundcovers (Paul et al., 1999; Whalen et al., 2000). Bare ground and CLT had large C_a and C_r pools but small C_s pools. This may reflect the prevalence of active and recalcitrant C pools in the applied compost or an inability of the soil microorganisms to convert compost C into C_s-C in these treatments. Bare ground also had the longest C_a MRT, suggesting active C was more protected from decomposition. Otherwise, the low initial C mineralization rate in BG may have resulted in the model incorporating a longer decomposition period into the C_a pool, overestimating the amount of C in that pool. Between the cover crops, NLC had greater C mineralization and larger C_a and C_s pools than LC. Differences in quality of plant litter, root exudates, and root turnover between legume and non-legume cover crop species may have affected the ability of soil microorganisms to degrade these residues (Booth et al., 2005).

Shorter MRT for C_a and C_s in soil under cover crops suggests more rapid decomposition and turnover of organic C inputs from cover crops. The weak correlation between MRT and C_s pool size indicates that the MRT of the C_s pool was affected more by treatment effects such as the composition of organic C input than by the size of that pool. Further research is needed to determine how different organic C inputs affect turnover rates of C_s-C. In contrast, a strong correlation between C_a pool size and MRT may show that larger C_a pools can persist where these materials are protected.

Injection of a soluble N fertilizer of fermented plant and animal waste increased soil inorganic N content in Sept. 2005 (Hoagland et al., 2008a). However, low soil N supply in Apr. 2006 in all treatments suggests this N was short-lived in the soil. Increasing the compost N application rate in 2006 and 2007 resulted in the greatest soil N supply in 2007. This may also be the result of the gradual release of N from the pelleted chicken manure applied in 2005 and the 2006 compost applications. In this study, compost N was applied near tree trunks and soil samples were taken beneath the compost application sites; therefore, total soil C and N increases were probably limited to the site of compost application.

Additions of wood chips and compost in WC increased total soil C, N, C_a-C, and C_s-C. The layer of decomposing wood chips may have been a favorable environment for earthworms. Elevated earthworm density may have increased C mineralization and the size of the C_a and C_s pools (Aira et al., 2008). We expected large organic C additions and a large C_a pool in WC to boost soil microbial activity; however, microbial biomass was not elevated. Wood chip mulch may favor specific species of fungi that break down lignin and other polyphenols (Yao et al., 2005), which may not be responsive to the glucose substrate used in the SIR method. Both WC treatments had low N supply in 2006. The wide C:N ratio and elevated C mineralization in WC likely resulted in N immobilization (Compton and Boone, 2002). However, N immobilization was not significant enough to negatively affect tree growth, yield, or leaf N. Increased fertilizer-use efficiency with wood chip and shredded paper mulch has been reported in other studies and may explain good tree performance in the WC treatments (Forge et al., 2003; TerAvest et al., 2010).

Incorporation of compost into the soil in CLT_{MCR} and CLT_{LCR} did not increase soil N supply over CON. Rapid C mineralization in

Table 5. Total soil C and N and C:N ratio from Sept. 2007 sampling and percent increase in C and N from Sept. 2005 to Sept. 2007 as affected by groundcover and compost rate.[z]

Groundcover	Compost rate	C (g C/kg soil)	N (g N/kg soil)	C:N	C (Percent increase)	N (Percent increase)
Control (CON)	None	9.8 d	1.0 d	9.6 def	–7 c	20 d
Bare Ground (BG)	MCR[y]	11.9 d	1.3 cd	9.2 defg	24 ab	77 bc
Brassica (BSM)	MCR	12.1 d	1.4 cd	8.9 efg	10 ab	54 cd
Cultivation (CLT)	LCR	10.0 d	1.1 d	9.4 def	11 b	55 cd
	MCR	12.6 d	1.5 cd	8.6 g	42 ab	115 abc
	HCR	18.6 bc	2.1 ab	8.8 fg	80 ab	180 ab
Wood Chips (WC)	MCR	20.0 ab	1.7 bc	10.8 b	104 ab	125 abc
	HCR	25.5 a	2.3 ab	11.2 a	99 ab	131 abc
Legume	LCR	11.9 d	1.2 cd	9.6 cd	46 ab	97 bc
Cover (LC)	MCR	13.2 cd	1.4 cd	9.5 def	8 b	51 cd
Non-legume	LCR	12.4 d	1.2 cd	10.5 bc	17 b	54 cd
Cover (NLC)	MCR	13.5 cd	1.4 cd	9.6 de	30 ab	79 bcd
	HCR	22.1 ab	2.4 a	9.2 efg	123 a	225 a
Mean		14.9	1.5	9.6	45	97

[z]Values within a column followed by the same letter are not significantly different ($P \leq 0.05$).
[y]HCR = high compost rate; MCR = medium compost rate; LCR = low compost rate.
C = carbon; N = nitrogen.

Table 6. Apple tree performance in 2007 as affected by groundcover and compost rate.[z]

Groundcover	Compost rate	Fruit yield (kg/tree)	TCSA[y] (cm^2)	Yield efficiency ($kg{\cdot}cm^{-2}$)	Leaf N (%)
Control (CON)	None	2.6 e	16.6 cde	0.14 h	2.87 cde
Bare ground (BG)	MCR[x]	13.1 c	16.6 cde	0.80 abc	3.00 abc
Brassica (BSM)	MCR	12.4 c	17.7 bcd	0.73 abcd	3.13 a
Cultivation (CLT)	LCR	13.8 bc	20.3 ab	0.69 cde	2.98 abc
	MCR	13.3 c	15.8 def	0.87 a	3.07 ab
	HCR	17.6 a	21.5 a	0.84 abc	3.10 a
Wood chip (WC)	MCR	14.1 bc	20.6 ab	0.69 bcd	3.09 a
	HCR	16.5 ab	20.0 abc	0.85 ab	3.04 abc
Legume cover	LCR	5.7 d	13.6 efg	0.43 fg	2.91 bcd
(LC)	MCR	6.7 d	12.7 fg	0.52 ef	3.08 ab
Non-legume	LCR	2.9 de	11.5 g	0.27 gh	2.77 de
Cover (NLC)	MCR	6.0 d	14.0 efg	0.41 fg	2.73 e
	HCR	8.0 d	14.9 defg	0.60 de	3.01 abc
Mean		10.2	16.7	0.60	2.98

[z]Values within a column followed by the same letter are not significantly different ($P \leq 0.05$).
[y]Trunk cross-sectional area.
[x]HCR = high compost rate; MCR = medium compost rate; LCR = low compost rate.

CLT_{MCR} may have resulted in N immobilization, which was observed in CLT_{MCR} after 7-d incubation in July 2007 (data not shown), reducing soil N supply. Additionally, soil disturbance reduced activity by both earthworms and AM fungi, consistent with other studies (Boddington and Dodd, 2000; Bohlen et al., 1999). Reduced activity by earthworms and AM fungi may have decreased stabilization of C into the C_s pool to serve as a source of inorganic N compared with other treatments. Reduced N supply in CLT_{LCR} and CLT_{MCR} did not negatively affect fruit yield or tree growth. Lack of alternative sinks for N in cultivated treatments has been shown to increase N use by young apple trees (TerAvest et al., 2010). Compost additions in CLT_{MCR} and CLT_{LCR} did not increase total soil C and N compared with CON. These results are in agreement with other studies showing that cultivation has detrimental effects on soil C and N (Beare, 1997, Van Den Bossche et al., 2009). At the high compost rate, total C and N increased significantly, and N supply was elevated in Apr. and Sept. 2007. These results are consistent with Whalen et al. (2008), who reported that large amounts of compost were needed to increase soil NO_3^- and total N in course-textured soil. Although fruit yield and tree growth were greatest in CLT_{HCR}, the high compost rate and elevated N supply may also increase the potential for N leaching losses.

Using herbicides to control weeds in BG reduced organic C inputs to the soil. Although BG had a seemingly large C_a pool, the C_a and C_s pools accounted for only 30% of total soil C, the lowest of all groundcovers. Low total soil C and N, earthworm density, AM fungi root colonization, and microbial biomass suggest a lack of substrate to drive microbial processes and stabilization of C into the C_s pool. Nitrogen supply was not low in BG relative to other groundcovers, but N immobilization was observed in July 2007 after 7-d incubation (data not shown). The rapid rate of C mineralization on a soil C basis and large C_a pool may have been responsible for this observed N immobilization (Barrett and Burke, 2000; Schaeffer and Evans, 2005). Despite low microbial activity in BG, fruit yields and tree growth were similar to BSM, CLT_{LCR}, CLT_{MCR}, and WC_{MCR}.

Applying brassica seed meal as a soil amendment along with herbicide weed control resulted in total soil C and N content, fruit yield, and tree growth similar to BG. In contrast, stabilization of C into the C_s pool, earthworm activity, and N supply in BSM were greater than BG. Increased N supply in BSM without a corresponding increase in total N indicates an increase in the proportion of N that was readily available. Nitrogen mineralization from an enlarged C_s pool, a greater earthworm population capable of enhancing N mineralization, and greater N content in the brassica seed meal (7% N) over compost (3.5% N) are the likeliest drivers of the observed increase in N supply (Aira et al., 2008; Whalen et al., 2000, 2001). Additionally, BSM has been reported as a readily mineralizable N amendment that increases the nitrifying bacterial population in soils (Balesh et al., 2005; Cohen and Mazzola, 2006). Nitrogen supply may have been excessive in this treatment, increasing the potential for N leaching losses to the environment.

Constant inputs of OC from plant litter, root turnover, and exudates from cover crops in LC and NLC increased microbial biomass and turnover of soil C compared with other groundcovers (Rovira et al., 1990; Wardle et al., 2001). However, tree performance, earthworm activity, and total C and N accumulation were low in LC and NLC at the low and medium compost rates. Moisture and nutrient competition between cover crops and apple trees likely reduced tree growth and fruit yield compared with other groundcovers, which is consistent with previous studies (Hoagland et al., 2008a; Marsh et al., 1996; Neilsen and Hogue, 1985; Sanchez et al., 2003). In addition to reducing tree performance, dry soil conditions have been reported to reduce earthworm activity (Parmalee et al., 1990). We expected competition between apple trees and non-legume cover crops to reduce N supply compared with LC treatments; however, N supply was similar between NLC and LC treatments. Greater root colonization by AM fungi in NLC may have aided in the decomposition of organic matter; increasing the size of the C_s pool has a source of mineralizable N and may have enhanced N mineralization compared with LC (Atul-Nayyer et al., 2009; Barea et al., 2005; Cochran et al., 2007). Despite similar soil N supply, greater leaf N in LC_{MCR} than NLC_{MCR} and NLC_{LCR} suggests that the legume cover crop may have contributed to apple tree N. Low leaf N in NLC_{LCR} and NLC_{MCR} suggests these treatments were N-deficient, affecting not only the apple trees, but also the cover crops. Nitrogen deficiency can reduce cover crop growth, reducing the supply of plant litter, root turnover, and exudates to the soil, further limiting N mineralization.

Groundcover management and compost rate had significant impacts on soil C partitioning, total soil C and N, microbial activity, N supply, fruit yield, and tree growth. Large compost additions significantly increased N supply under cultivation and non-legume cover crops but not under wood chip mulch. Brassica seed meal increased C_s-C, soil N supply, and earthworm activity without improving fruit yield or tree growth. Greater stabilization of C into C_s may increase the sustainability of BSM and its ability to supply N long term, but quick release of inorganic N in this system may also result in large N leaching losses. Further research and development is needed to match application timing of brassica seed meal amendments with N release to meet apple tree needs. Cultivation plus the high compost rate resulted in the greatest fruit yield and elevated N supply; however, the added expense of large compost additions as well as the potential for increased N leaching losses makes this compost rate economically and environmentally unsustainable. Cultivation resulted in low C_s-C, earthworm population, and AM fungi root colonization and would likely result in a loss of soil fertility over the long term. Similar to CLT, the bare ground treatment had adequate yield in the short term, but little stabilization of C into the C_s pool and low biological activity may reduce long-term soil fertility. The use of cover crops increased C_s-C, soil N supply, and microbial biomass, but competition between apple trees and cover crops for nutrients and possibly water severely reduced fruit yield and tree growth making cover crops unsuitable for orchard establishment. Wood chip mulch increased both active and slow soil C pools, total soil C and N, earthworm activity, fruit yield, and tree growth despite lower soil N supply. This system appears to be more capable of improving soil properties and increasing production than other systems in this study.

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